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Convergence Analysis of the Numerical Solution for Cathode Design of Aero-engine Blades in Electrochemical Machining

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Abstract

As a main difficult problem encountered in electrochemical machining (ECM), the cathode design is tackled, at present, with various numerical analysis methods such as finite difference, finite element and boundary element methods. Among them, the finite element method presents more flexibility to deal with the irregularly shaped workpieces. However, it is very difficult to ensure the convergence of finite element numerical approach. This paper proposes an accurate model and a finite element numerical approach of cathode design based on the potential distribution in inter-electrode gap. In order to ensure the convergence of finite element numerical approach and increase the accuracy in cathode design, the cathode shape should be iterated to eliminate the design errors in computational process. Several experiments are conducted to verify the machining accuracy of the designed cathode. The experimental results have proven perfect convergence and good computing accuracy of the proposed finite element numerical approach by the high surface quality and dimensional accuracy of the machined blades.

Keywords: electrochemical machining; aero-engine blade; cathode design; convergence analysis

1 Introduction

With the rapid progresses of aero-engine performance, the machining quality and dimensional accuracy of aero-engine blades become ever-increasing important. In order to obtain excellent aerodynamic performance, the shape of aero-engine blades turns more and more complex. In addition, because of their high strength, high temperature stability, and high corrosion resistance, hard passive alloys, such as nickel-based superalloys, titanium alloys and molybdenum alloys have found wider application than ever as aero-engine blade materials, for which traditional machining methods of manufacturing aero-engine blades such as electro-discharge machining, die casting, forging and numerical control machining might result in poor surface quality, residue stresses and surface micro-cracks[1-4]. In comparison with them, electrochemical machining (ECM), by using anodic dissolution to shape metal, has been developed to machine high-strength, heat-resistant alloys, which are otherwise extremely difficult to be worked by conventional methods, to which, naturally, ECM has turned to be the ideal alternative in aeronautic and astronautic industries, particularly in production of aero-engine blades. Fig.1 shows a selection of aero-engine blades produced by ECM[5-7].

However, further application of ECM is limited by the difficulties in tool (cathode) design and process monitoring.

In ECM, cathode design is to fix the shape of a cathode to produce a required shape of workpieces.

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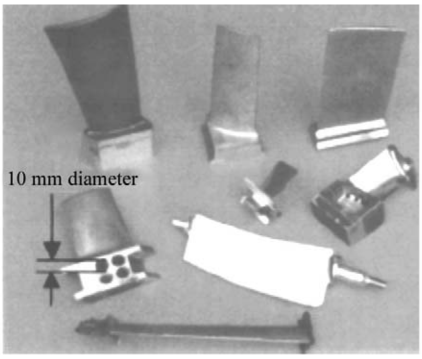


Fig.1 ECM aero-engine blades.

Rapid advancements in computer and numerical technologies have rendered it possible to develop a more complicated approach of cathode design. Current efforts are primarily made to address this issue based on the Laplace equation for potential distribution in inter-electrode gap by using numerical solutions. Various numerical solutions such as boundary element, finite difference and finite element have been applied to the cathode design in ECM. Among them, finite element method presents more flexibility to deal with the irregularly shaped workpieces[8-12]. However, it is not easy to ensure the convergence of the finite element method. By taking an aero-engine compressor blade as the object (model blade) of the research shown in Fig.2, this paper proposes an accurate model and finite element numerical approach for the cathode design of blades in ECM based on the potential distribution in inter-electrode gap. All boundary conditions which should be satisfied in the numerical approach are analyzed. In order to ensure the convergence of this numerical approach and increase the accuracy of cathode design, the cathode shape should be iterated in computing process to eliminate the errors. Finally, experiments for verification have been conducted with satisfied results.

2 Principle and Model of ECM

Fig.3 shows the schematic diagram of ECM system. The ECM process connects the workpiece (anode) to the tool (cathode) via an electrolytic cell, through which an electrolyte is pumped. A low DC voltage of 10-20 V is applied across the gap between the tool and the workpiece. A high ampere current (30-200 A/cm^2) is made to pass the gap through electrolyte flowing at high speed of 6-30 m/s. The anode material dissolved electrochemically is flushed away by flowing electrolyte. By feeding the tool continuously, the shape of the workpiece is becoming a mirror of the tool electrode. In an ECM process, the inter-electrode gap distribution depends on electric filed distribution in function of many process parameters, which vary in space and time during electrochemical dissolution process. Fig.4 shows the integrated mathematic model of electric field distribution within ECM gap domain Ω[13-15].

Based on the ECM fundamental theories, the electric potential distribution within Ω can be described by Laplace equation

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=0 \tag{1}$$

According to Faraday's law and Ohm's law, anode and cathode boundaries should satisfy par-

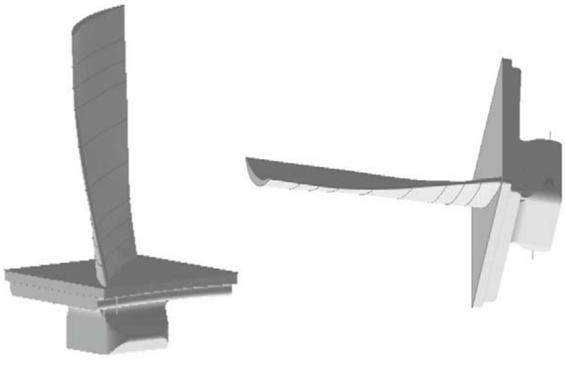


Fig.2 Solid model of an aero-engine blade.

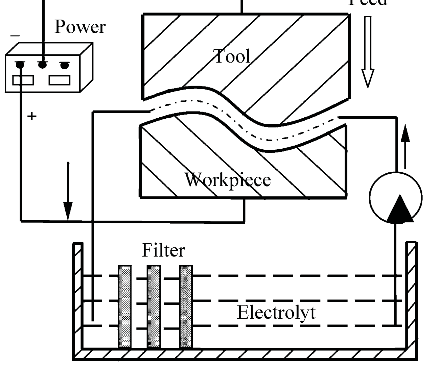


Fig.3 Schematic diagram of ECM system.

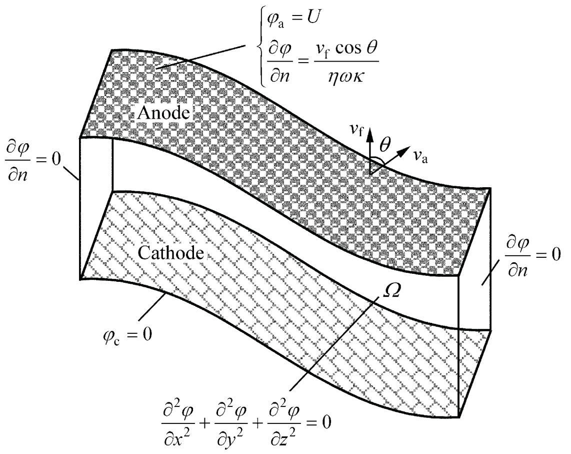


Fig.4 Electric field distribution within ECM gap.

ticular machining conditions expressed by

$$\frac{\partial\varphi}{\partial n} = \frac{v_f}{K_v\kappa}\cos\theta \quad \text{on anode boundary} \tag{2}$$

$$\varphi_a = U \quad \text{on anode boundary} \tag{3}$$

$$\varphi_c = 0 \quad \text{on cathode boundary} \tag{4}$$

where φ is the electric potential within Ω, φ_a the anode electric potential, φ_c the cathode potential, U the applied voltage, v_f the feed rate of cathode, η the current efficiency, K_v the volumetric electrochemical equivalent of anode metal, κ the electrolyte conductivity (constant), θ the angle between the normal to the anode and the feed direction of cathode. The aim of cathode design is to find a cathode boundary which can satisfy Laplace equation for the electric potential distribution within ECM gap domain Ω and also all boundary conditions listed in Eqs.(1)-(4). This can be achieved by specific numerical solution, which will be discussed below.

3 Finite Element Numerical Solution for Cathode Design

As mentioned above, the aero-engine blade shown in Fig.1 should be regarded as a workpiece, i.e., an anode in ECM. The general process of numerical solution based on finite element (FE) method are summarized in following three stages:

(1) To form an initial ECM gap domain. An approximate initial cathode boundary (shape) can be achieved with the “cos θ method”. Combining this initial cathode shape and the blade shape forms the enclosed ECM gap domain Ω. Failing to satisfy those boundary conditions mentioned above though, the initial cathode shape provides an enclosed gap domain as an analysis model in FE.

(2) FE model. Ω is divided into small hexahedron elements, as shown in Fig.5. There are five layers in Ω with mn (n lines×m columns) being the number of nodal points at each layer. A potential function $\varphi(x, y, z)$ that varies linearly inside each hexahedron element is defined as

$$\varphi(x,y,z) = \sum_{i=1}^{8} N_i(x,y,z)\varphi_i \tag{5}$$

where $N_i(x, y, z)$ (i=1,2,···,8) is a linear functions of x, y and z, which can be expressed by

$$N_i(x,y,z) = a_i + b_i x + c_i y + d_i z + e_i xy + f_i yz + g_i xz + h_i xyz \tag{6}$$

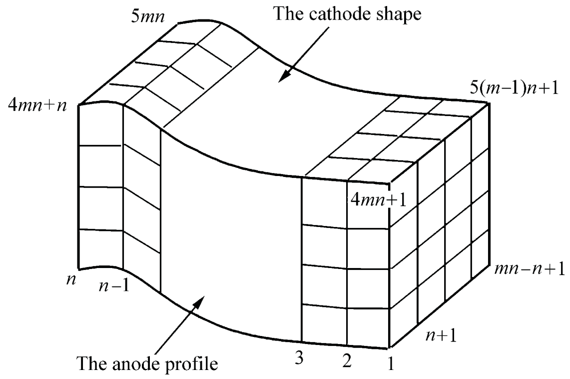


Fig.5 Meshing and numbering elements.

According to FE computing method, the coefficient matrix of each element, $\boldsymbol{K}^e$, can be calculated as

$$\boldsymbol{K}_{ij}^e = \iiint_{V^e} \left(\frac{\partial N_i^e}{\partial x}\cdot\frac{\partial N_j^e}{\partial x} + \frac{\partial N_i^e}{\partial y}\cdot\frac{\partial N_j^e}{\partial y} + \frac{\partial N_i^e}{\partial z}\cdot\frac{\partial N_j^e}{\partial z} \right) \mathrm{d}V \tag{7}$$

Assembling all elements coefficient matrix together can be given

$$\begin{bmatrix} \boldsymbol{k}_{11} & \boldsymbol{k}_{12} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{k}_{21} & \boldsymbol{k}_{22} & \boldsymbol{k}_{23} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{k}_{32} & \boldsymbol{k}_{33} & \boldsymbol{k}_{34} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{k}_{43} & \boldsymbol{k}_{44} & \boldsymbol{k}_{45} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{k}_{54} & \boldsymbol{k}_{55} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{\varphi}_1 \\ \boldsymbol{\varphi}_2 \\ \boldsymbol{\varphi}_3 \\ \boldsymbol{\varphi}_4 \\ \boldsymbol{\varphi}_5 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b}_1 \\ \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{0} \\ \boldsymbol{0} \end{bmatrix} \tag{8}$$

where $\boldsymbol{k}_{ij}$(i, j=1,2,···,5) is mn×mn matrix with nonzero determinants assembled from $N_i(x, y, z)$, $\boldsymbol{\varphi}_i$ (i=1,2,···,5) the column vector potential. Particularly, $\boldsymbol{\varphi}_1$ and $\boldsymbol{\varphi}_5$ are column vectors of potential at the blade shape and cathode shape respectively. $\boldsymbol{\varphi}_2$ to $\boldsymbol{\varphi}_4$ are center gap potential and $\boldsymbol{b}_1$ is the column vector generated by path integration in

$$\iint \frac{v_{\mathrm{f}}}{K_{\mathrm{v}} \cdot \kappa} \cos\theta \cdot \varphi \mathrm{d}s \tag{9}$$

(3) Boundary condition treatment and cathode shape selection. One boundary condition on anode (blade) shape is applied in Eq.(9) by calculating $\boldsymbol{b}_1$, another boundary condition, $\varphi_{\mathrm{a}} = U$, is also applied by letting all elements in vector $\boldsymbol{\varphi}_1$ equal U in Eq.(8). Thereafter, Eq.(8) can be solved successfully, which means the electrical potential distribution within Ω can be determined. From the known potential distribution, may be found several equi-potential shapes, out of which an appropriate one can be selected as the cathode shape according to actual machining parameters.

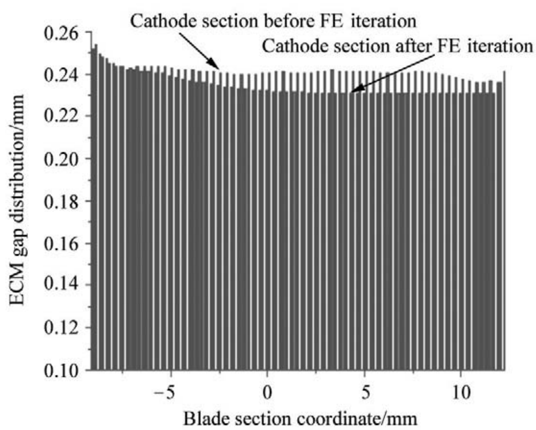
4 Convergence Analysis of FE Algorithm

In principle, the FE numerical solution for cathode design of aero-engine blades mentioned above does not need iteration. After computation, the potential distribution in ECM gap will satisfy the Laplace equation and all boundary conditions. Though all these equi-potential shapes found from the known potential distribution are the cathode shapes required, their potential distribution in ECM gap is not stable and, moreover, these equi-potential shapes are not precise. This means the need for improvement of convergence of this FE numerical solution. The main causes that affect convergence of FE numerical solution can be summarized as follows:

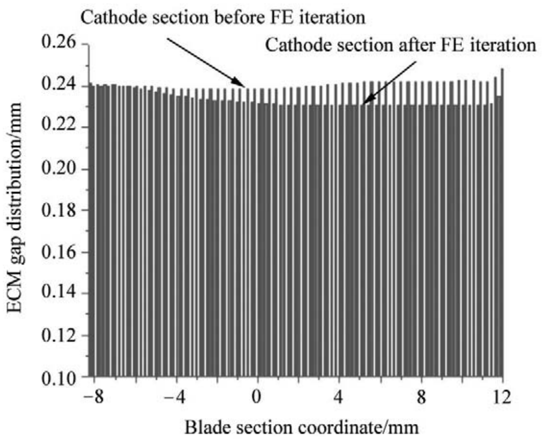
(1) The problem of boundary insulation. According to FE numerical solution, it is considered that the ECM gap boundaries have been insulated, as shown in Fig.4. However, in actual ECM process, all gap boundaries are "open", meaning absence of insulation.

(2) Curvature change. Because the pressure side and suction side of the model blade are very "sharp", a momentous change of curvature happens at blade edges, which may results in excessive deformation of hexahedron elements. All these will reduce the computing accuracy of potential distribution in ECM gap domain, which in turn affects the cathode boundary. Therefore, in order to improve computing accuracy and accelerate convergence of the FE method, might be taken the following steps: ① to work out and implement an FE cathode design program to obtain some equi-potential shape. The initial cathode boundary generated by "cos θ method" requires to be replaced by a selected cathode shape (an equi-potential shape); ② to repeat the FE cathode design program after the initial cathode boundary has become an equi-potential shape selected in above step to adjust the cathode boundary; ③ repeat step ② till the adjusted amplitude of cathode boundary is no more than the designated value, for example, 0.5%. This means a stable potential distribution in ECM gap domain and a cathode boundary.

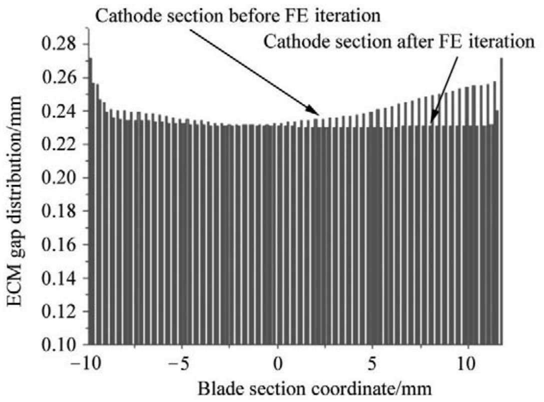
As mentioned above, every step of iteration can increase the design accuracy of cathode shape and accelerate convergence of FE algorithm. The rapid convergence of FE algorithm is vital to obtain a high quality cathode shape. Slow convergence of FE algorithm in cathode design makes lead-time and machine downtime longer and cost higher. The FE computing program generally takes about one hour for iterating 3-5 times to obtain an appropriate cathode shape. Fig.6(a), (b), (c) and (d) show four sections from sixty shape cathode boundaries in an



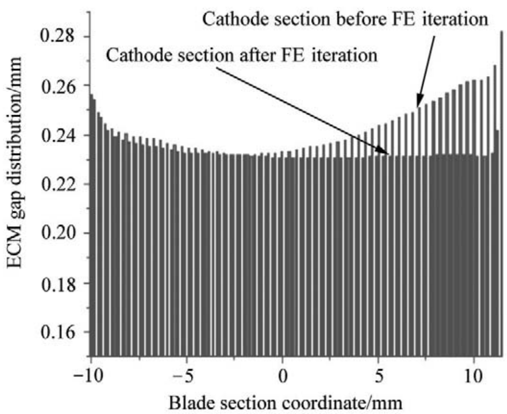
(a) Cathode section 10



(b) Cathode section 20



(c) Cathode section 30

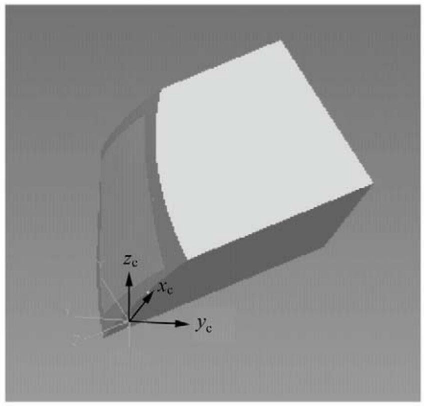


(d) Cathode section 40

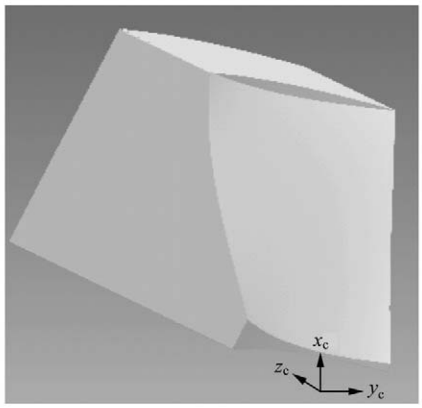
Fig.6 Comparison of cathode sections before and after iteration with FE algorithm.

attempt to make a comparison of them before and after iteration with FE algorithm.

From Fig.6, it is clear that FE iteration algorithm for cathode design of blade is able to effectively improve design accuracy of the cathode shape. After iteration, the sections of cathode shape become more smooth and stable, which in turn make the potential distribution in ECM gap domain more stable. Fig.7(a) and (b) are the solid models of cathode shape designed for machining pressure side and suction side of the model blade (as shown in Fig.2) respectively. The two cathode models were completed on UG software platform.



(a) Cathode shape on pressure side of blade



(b) Cathode shape on suction side of blade

Fig.7 Disigned cathode shapes for the model blade.

5 Experimental Work

In order to verify the design accuracy of cathode shape, machining experiments on the pressure side of model blade were conducted on an industry-use ECM machine, Model JAPAX-300B, as shown in Fig.8. Prior to machining experiments, a specific cathode tool was made. Then the cathode model, shown in Fig.7(a), was incorporated into a CAM system to produce a digital profile, which was set into the controller of a CNN machine. Thus the required cathode tool can be machined out of stainless steel 1Cr18Ni9T in accordance with the digitized data, as shown in Fig.9. Fig.10 shows the machined blade samples. According to the requirements, among the given nine sections of model blade, each one's dimension should be within 0.12 mm of any other one's. The final measure results of each section of two blade samples are plotted on Fig.11(a) and (b), which evidence an entire agreement between all of the measured data and the dimension accuracy requirements. This in turn proves the presented numerical solution in cathode design is valuable to produce a required tool shape, and therefore, improve ECM process performance.

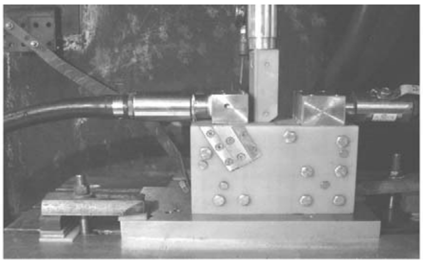
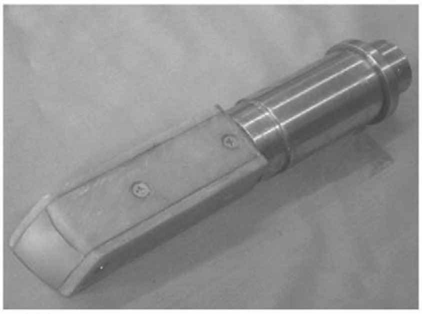


Fig.8 Machining experiment of ECM.

(a) Cathode shape (no insulation)



(b) Cathode shape insulated by epoxide resin

Fig.9 Cathode tool for the pressure side of model blade.

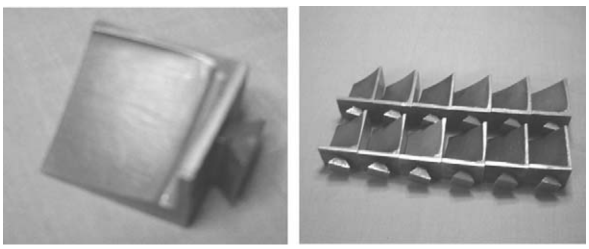
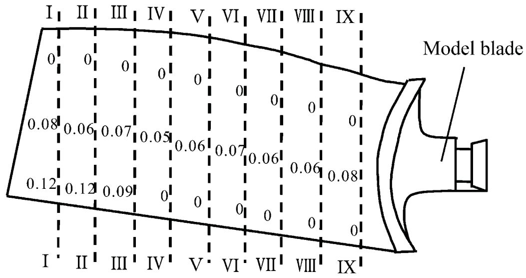
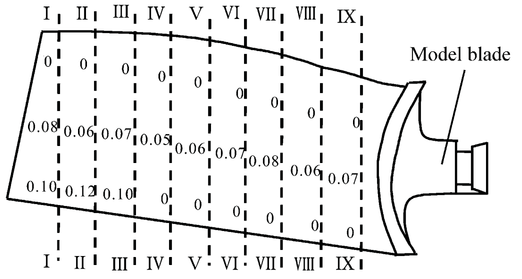


Fig.10 Experimental samples of machined blades.



(a) Measured data of given sections of sample *A*



(b) Measured data of given sections of sample *B*

Unit: mm

Fig.11 Measured data of dimensional accuracy of given nine sections.

6 Summary and Conclusions

A numerical solution for cathode design of aero-engine blades in ECM is proposed. The essential of this approach is to find an appropriate cathode (tool) shape, which can satisfy the Laplace equation for electrical potential distribution in ECM gap domain and all other electrode boundary conditions to achieve the desired blade shapes and sizes. Moreover, the convergence of this FE numerical solution has been discussed in detail. In order to verify the machining accuracy of the designed cathode, the experiments have been conducted. The experimental results demonstrate that the machined blades have high surface quality and dimensional accuracy. This proves the proposed FE numerical approach has good convergence and computing accuracy.

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Biography:

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